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Speed Choice, Speed Variance, and Speed Limits

A Second-best Instrument to Correct for Road Transport Externalities

Piet Rietveld and Daniel Shefer*

1. Introduction

Governments have at their disposal two main types of instruments to contain the external effects of transport: standards, and taxes (see Baumol, 1972; Baumol and Oates, 1988). While taxes are to be preferred from an efficiency viewpoint, it is nevertheless striking that standards are used more frequently. This also holds true for policies with respect to travel speeds: as far as speed is concerned, standards (speed limits) are in use almost universally in road transport. This note will address a number of issues concerning speed limits in road transport; in particular it will discuss their potential to solve the problems related to the gap between private and social costs of transport.

Our point of departure for the analysis of speed limits will be a certain trip from A to B for a certain driver. We will assume that the route of the trip is given, that the driver is in principle free to choose his speed, and that the route is homogeneous so that the speed can be constant during the trip. The optimum speed level depends on a variety of factors such as:

- travel time costs;
- costs of arriving late (or early);
- monetary costs of driving;
- costs of accidents;
- costs of fines, enforcement;
- utility of driving *per se*; and
- various external costs such as noise, particulates, and emissions.

Some of the cost components mentioned here are entirely private, others are partially (safety) or entirely (for example, emissions) external. One of the aims of transport policies is to achieve appropriate levels of external costs. This is partly done by a combination of standards and taxes with respect to the technology of the cars and the fuel used.

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However, the standards and taxes are usually applied in such a way that they are not directly addressing the actual levels of external effects. The reason is that some of the external effects also depend on driver behaviour, which is not directly affected by such standards or taxes. An important component of driver behaviour is the choice of speed. It is to this aspect of driver behaviour that the present paper will be addressed.

In Section 2 we introduce private and social costs of trips as a function of speed. Implications for speed choice and speed regulation by means of maximum speed limits are discussed. Special attention is paid to the case of heterogeneous drivers. In Section 3 the analysis is extended to the case where private and social costs of trips are dependent on speed variance. In this case both maximum and minimum speed limits have to be considered.

2. Social Versus Private Optimum Speed

2.1 Individual level

Consider an individual car driver. The private costs CP_i of a certain trip i depend on the features of the driver, the car, the road, external conditions (weather, and so on), and the trip purpose (these features are represented by a vector x_i), as well as on the speed (s_i) chosen:

$$CP_i = CP_i(x_i, s_i). \quad (1)$$

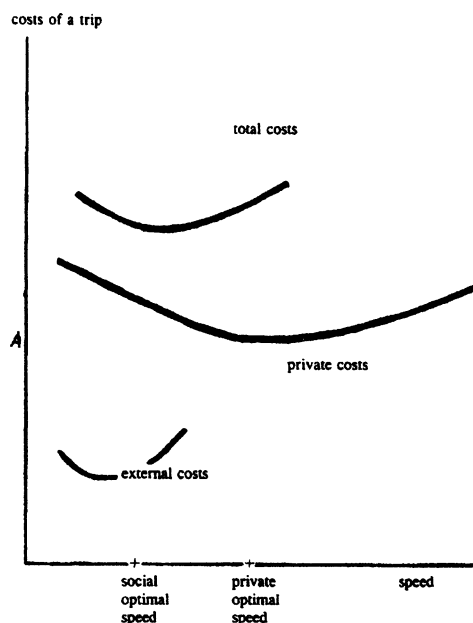
In the literature we find that important factors among x_i are personal features of drivers such as age, gender, and income (Jorgenson and Polak, 1993; Rienstra and Rietveld, 1996). That income is a relevant factor in speed choice is credible, since income is an important determinant of the value of time (HCG, 1990). The private cost curve is assumed to be a convex and U-shaped function of speed, with an optimum speed sp_i^* leading to a finite minimum value of the private costs (see Figure 1). The U-shaped curve for the private costs is plausible. For low speeds the costs are dominated by the time cost component, which is very high within that range. The reason is that time costs are proportional to travel time T , which is inversely related to speed, since by definition $T = d/s$, where d denotes distance travelled. Note that an increase in speed of 1 km/h leads to a much higher decrease in travel time for low speeds than it does for high speeds. Therefore for high speeds the marginal time costs are much smaller, and the role of factors such as fuel costs becomes much more important (fuel use per kilometre travelled starts to increase sharply at speeds above 80 kmph; see Klein, 1993).

In a similar way, the external costs CE_i of a certain trip depend on some of the above mentioned factors, where especially the vehicle features are relevant:

$$CE_i = CE_i(x_i, s_i). \quad (2)$$

The external costs tend to be an increasing function of speed: at higher speeds noise annoyance and emissions are higher than at lower speeds. However, at very low speeds the environmental performance of cars may be worse than at moderate speeds (see for example TRB 1995, Chapter 2). Thus we again see a convex U shaped curve.

Figure 1
Socially Versus Privately Optimum Speed



In addition, social costs CS_i are defined as the sum of private and external costs:

$$CS_i = CP_i + CE_i \quad (3)$$

Assume that the individual is free to choose his or her speed by minimising private costs. The resulting private optimum speed sp_i^* is in general not equal to the social optimum speed ss_i^* resulting from the social cost function. Given the shapes of the private and social cost curves, one will in general find:

$$ss_i^* < sp_i^*.$$

In order to reach the social optimum speed, there are two main possibilities to influence individual speed choice: pricing and speed standards.¹

¹ We will not discuss other main measures to influence speeds, such as infrastructure adjustment to achieve traffic calming, and changes in communication technology. These measures lead to changes in the factor x_i in cost equations. In this paper we will assume that x_i is given.

Optimal *pricing* of speed would mean that the driver pays a certain amount of money per additional speed level equal to the marginal external costs in the social optimum. Such a pricing scheme does not exist in reality, one of the reasons being that it is difficult to implement. Another approach would be that taxes would not be attached to speed as such but directly to the external effects. For example, by paying a petrol tax, drivers pay for the CO₂ emission (Sterner *et al.*, 1992; Eskeland, 1994) so that this part of the external effects is already internalised when drivers choose their optimum speed.² However, with other external effects such as safety and noise, it is very difficult to find a tax base that more directly touches the final negative external effect.

The second possibility of *speed standards* has received almost universal acceptance. Assuming strict obedience to speed standards, the optimum speed limit would be ss_i^* . However, speed standards are not automatically obeyed. Therefore, speed limits need to be complemented by a system of surveillance and fines in order to enforce socially optimal speed choice.

Let $f(s)$ be the level of the fine, and p the probability that a driver is caught during a certain trip. This probability may depend on the speed itself, but without loss of generality we ignore this possibility. Then, the level of the fine should satisfy the following condition:

$$CP_i(s_i) + p \cdot f(s_i) > CP_i(ss_i^*) \quad \text{for all } s_i > ss_i^*. \quad (4)$$

For convenience of notation we remove the determinant x_i from the cost functions. When the probability of being caught while speeding is equal to 1, any fine higher than the difference between the private costs at a certain speed and the private costs at the social optimum suffices to induce the driver to drive at the socially optimum speed. Thus the fine would have to be higher than the difference between level A in Figure 1, and the actual private costs, taking into account the probability of being caught. The conclusion is that in the context of speed policies the difference between standard setting and pricing is smaller than is often thought. Standard setting is not effective without a system of fining, and fining can be interpreted as setting a stochastic speed-dependent price. Further reflections on speed taxes and fines are given in Appendix 1.

2.2 Heterogeneous drivers

The above analysis was carried out at the level of the individual driver. However, the generalisation towards a collective of drivers is by no means straightforward when we assume that drivers are heterogeneous. The point is that when drivers have different cost curves their optimum speeds will be different.

Minimisation of the total social costs:

$$\sum_i CS_i(x_i, s_i) = \sum_i [CP_i(x_i, s_i) + CE_i(x_i, s_i)] \quad (5)$$

² Note, however, that an information problem exists because many drivers are not aware that their petrol consumption depends on speed. In Section 3 attention will be paid to information provision on costs.

would imply that each individual i travels at his or her own socially optimum speed. For example, other things being equal, people with a high value of time will travel faster than other people (see, for example, Rienstra and Rietveld, 1996).

When a uniform speed limit is applied, it will be impossible to take into account this variety among drivers. This indicates that in the case of heterogeneity, maximum speed limits only have a second-best character. A more detailed account of the issues involved is given in Appendix 2. One of the results is that in the case of heterogeneity, one may arrive at a non-convex relationship between maximum speed limits and aggregate social costs. Non-convexity implies that the imposition of an optimal maximum speed limit is no longer trivial.

3. Speed Choice and Speed Differences

In the analysis in Section 2 we ignored the interrelationships between the speed choices of different drivers: drivers are assumed not to hinder each other; nor do they voluntarily adjust their speed to the speeds of other drivers. Such interrelationships are relevant, however, since in the context of safety the difference between the speed of driver i and the speeds of the other drivers plays a role in the cost functions. The issue of the link between speed variance and accident rates was first studied by Solomon (1964).

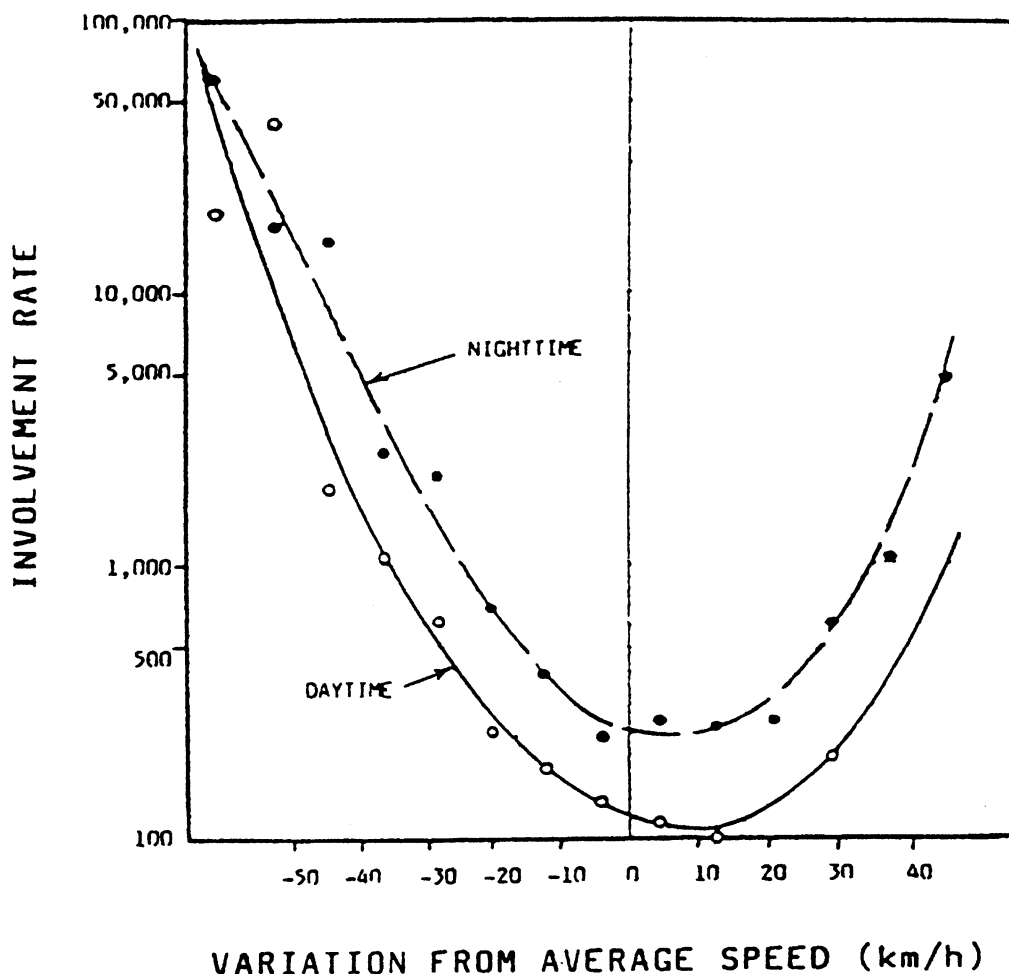
Solomon argued that the relationship between car accidents and the speed of travel can be described by a U-shaped curve (see Figure 2). As can readily be discerned, variations around the average speed of travel, above or below, are associated with an increase in the rate of car accidents. The background of this result is that the rate of car accidents is closely linked to the number of overtakings, and overtakings are closely related to speed differences (see also Hauer, 1971). Solomon's findings were subsequently corroborated by several other studies, including that of Lave (1985), which sparked a debate in the American Economic Review (see Levy and Asch, 1989; Fowles and Loeb, 1989; and Snyder, 1989). Further reviews are given by Fildes and Lee (1993) and Finch *et al.*, (1994).

We conclude that the higher the speed differences, the higher the probability that a driver will be involved in an accident. The question in the present context is to what extent these speed-difference related costs are internal or external. This question is important, since those speed differences that lead to external costs would be a source of unnecessarily high levels of social costs of transport.

To analyse the internal versus external character of speed variance related costs we consider the case of I drivers on a highway. We assume that congestion is not a real problem: in that case choice of speeds would no longer be an interesting issue. Assume that private costs are a second degree polynomial of speeds and of speed differences:

$$CP_i = \alpha s_i^2 - \beta_i s_i + \gamma_i + \eta \sum_{j \neq i} (s_i - s_j)^2 / (I - 1) \quad (6)$$

Figure 2
Solomon's U-Shaped Curve of Car Accidents as they Relate to Traffic Speed Variance



where the parameters α , β_i , and η are assumed to be positive. The first three terms correspond to the private cost function as introduced in Section 2. The accident costs of single-car accidents are included in the terms $\alpha s_i^2 - \beta_i s_i + \gamma_i$. The last term in this equation refers to the costs of two-car accidents; it represents the impact of speed differences on private costs of driving of driver i . Then the optimum private speed of driver i (given the speeds of the other drivers) is:

$$sp_i^* = (\beta_i + 2\eta s_i^-) / (2\alpha + 2\eta), \quad (7)$$

where s_i^- denotes the average speed of all drivers except i . The average speed s^- across all drivers can easily be shown to equal:

$$s^- = (1/I) \sum \beta_i / (2\alpha). \quad (8)$$

Thus the average speed does not depend on the speed-variance parameter η . Hence the introduction of the speed-difference term in the private cost function does not affect the average speed preferred by drivers. Note that without the speed interaction term in the private cost function the average speed is indeed $(1/I) \sum \beta_i / (2\alpha)$.

In addition, an investigation of the variance reveals that the introduction of the speed difference term leads to a lower variance in speeds when $\eta > 0$. Thus, with the above equation, the introduction of interrelationships in speed choices of drivers does not change the *average* privately preferred speed of drivers, but it does lead to smaller speed differences, and hence higher safety of the drivers.

An important question to be considered is whether with the above adjustment of speed the socially optimum level of safety is achieved. The answer is negative; we will show that minimisation by each individual driver of CP_i with respect to speed s_i does not lead to socially optimum speeds. The basic reason is that with individual minimisation of the private cost functions the impact of speed s_i on the risk of the other drivers does not play a role in the decision of driver i . This driver only adjusts his speed on the basis of the effect of speed on his own safety. Joint minimisation of $\sum_i CP_i$ with respect to all s_i would lead to socially optimum speed values:³

$$ss_i^* = (\beta_i + 4\eta s_i^-) / (2\alpha + 4\eta). \quad (9)$$

Comparing equations (9) and (7) we note that the introduction of safety related to speed differences in the *social* cost function again does not affect the average speed. However, the socially optimum speeds and the privately optimum ones are not identical. The difference between the two speeds is that the variance of the privately optimum speeds is larger than the variance of the socially optimum speeds. Note that the weight of η is larger in ss_i^* than in sp_i^* . The larger this weight the smaller the variance. Note also that when β_i and α are small relative to η the speed of all drivers will approximately be the same leading to a near zero speed variance. Thus, in the social optimum the speeds are more strongly adjusted towards the average than in the private optimum. In the social optimum fast drivers will drive more slowly than otherwise, while slow drivers will drive more quickly. This is an important difference compared with the type of externality considered in Section 2 where the socially optimum speeds are *lower* than the privately optimum speeds.

An illustration of these results is given in Table 1. Suppose there are three equally large groups of drivers ($i = 1, 2, 3$). Their corresponding β parameters are 150, 200, 250;

³ For clarity of presentation we assume here that the external cost component only relates to the speed interaction term; as mentioned in Section 2, other related costs are not included here. This assumption will be relaxed below.

α equals 1. When the speed variance parameter η equals zero, the corresponding optimum speeds are 75, 100, and 125 kmph, respectively. When costs are indeed dependent on speed variance (say $\eta = 0.25$), the privately optimum speeds partly converge towards 80, 100, and 120 kmph. However, because of the externality involved, convergence is not enough to achieve the social optimum values based on equation (9): 83.3, 100, and 116.7 kmph.

Further inspection of the cost levels reveals that it is the medium group of drivers that benefits most from the transition from sp_i^* to ss_i^* . This is no surprise, since in the present example this group does not need to change its speed, so that it can benefit from the change in other drivers' behaviour without the need of a change in its own behaviour. But the other groups of drivers also appear to be net beneficiaries in this example.

How would maximum speed limits affect the performance of road traffic? It is not difficult to see that a speed limit does not only affect the drivers with individually desired speeds above the limit, but also all other drivers. As shown in Table 1, the other drivers would adjust their speeds in a downward direction. This means that the slow drivers adjust their speed into the wrong direction (where the term 'wrong' is used from the perspective of social costs). Therefore, when safety is connected to speed differences, a maximum speed limit is not very satisfactory. However, a combination of a maximum speed limit with a minimum speed limit would be more effective, as shown in the last line of the table.

When we inspect the cost levels again, we observe that the introduction of the maximum speed limit (compared with the privately optimum case) leads to a cost increase for the fast drivers, and a decrease for the other drivers. The slow drivers especially appear to be better off: their costs are even lower than in the case of the social optimum (169.1 versus 185.1). Yet the last line shows that the introduction of a minimum speed limit (in addition to a maximum speed limit) would decrease total costs. This is in harmony with the conclusion of Hauer (1971, p.7): "the indiscriminative public crusade against speeding should be replaced by a balanced approach emphasising the dangers of both fast and slow driving".

Obviously, the table illustrates a simplified case with only three groups of drivers. However, when a more continuous distribution of privately preferred speeds exists, the mechanism with a maximum and a minimum speed limit still works. In principle one could finally arrive at a distribution of speeds with substantial numbers of drivers driving at the minimum and maximum speed limit, and the others driving near their privately preferred speed. This does not exactly coincide with the social optimum, since in the social optimum all drivers would adjust their speeds from sp_i^* to ss_i^* , as given above. However, in real world settings the combined effect of a minimum and a maximum speed limit may be satisfactory.

In the above analysis we assumed that drivers are aware of the speed-variance dependent costs. It is not impossible that although these costs are real, they are nevertheless not (or not fully) perceived by the drivers. Drivers may not understand the underlying mechanism, so they may be unaware that they can influence the speed vari-

Table 1
*Speed Choice of Various Groups of Drivers
 under Various Regimes of Speed Regulation*

<i>Regime</i>	<i>Speed in kmph:</i>			<i>Total costs</i>	<i>Average speed in kmph</i>	<i>Speed variance in kmph²</i>
	<i>slow drivers</i>	<i>medium drivers</i>	<i>fast drivers</i>			
	<i>(costs in parentheses)</i>					
No speed variance dependent costs	75 (0)	100 (0)	125 (0)	0	100	417
Speed variance dependent costs; private optimum sp_i^*	80 (191.7)	100 (66.7)	120 (191.7)	450	100	417
Speed variance dependent costs; social optimum ss_i^*	83.3 (185.1)	100 (46.5)	116.7 (185.1)	416.7	100	185
Speed variance dependent costs; maximum speed of 116.7 kmph; private optimum	79.8 (169.8)	99.8 (57.2)	116.7 (206.2)	433.2	97.2	294
Maximum speed of 116.7 kmph; minimum speed of 83.3 kmph; private optimum	83.3 (185.1)	100 (46.5)	116.7 (185.1)	416.7	100	185

Note: for costs, a reference value zero has been chosen in the upper row.

ance related costs by their speed choice. In that case the drivers will not adjust their speeds in view of speed differences (see Table 2). The consequence would be that all speed variance related costs are considered external. This leads to higher variances and cost levels. The gain in terms of total costs of a maximum and a minimum speed limit is larger here than in the case of Table 1. All drivers would gain in each of the successive steps of introducing maximum and minimum speed limits.⁴

Comparison of Tables 1 and 2 indicates that lack of information about the risks of driving considerably slower (or faster) than the average driver leads to a larger number of accidents and a higher cost level. An alternative strategy to the imposition of minimum speed limits would therefore be to provide information to road users about these risks. By comparing the first lines of both tables, we see that when drivers become aware of these risks they adjust their behaviour into the right direction. However, as long as the external part of the speed-variance costs are not taken into account, information alone is not enough to arrive at the social optimum. The speed adjustments simply do not go far enough.

⁴ Note the difference with Table 1, where fast drivers experience a cost increase as a result of the introduction of a maximum speed limit. In Table 2 fast drivers would gain from such an introduction.

Table 2
*Speeds and Transport Costs of Various Groups of Drivers under
 Various Regimes of Speed Regulation where Speed Variance Dependent Costs
 are Assumed to be Unperceived by Drivers*

Regime	Speed in kmph:			Total costs	Average speed in kmph	Speed variance in kmph ²
	slow drivers	medium drivers	fast drivers			
	(costs in parentheses)					
No speed variance dependent costs	75 (0)	100 (0)	125 (0)	0	100	417
Speed variance dependent costs present but not perceived; private optimum	75 (260.4)	100 (104.2)	125 (260.4)	625	100	267
Speed variance dependent costs; social optimum	83.3 (185.1)	100 (46.5)	116.7 (185.1)	416.7	100	185
Speed variance dependent costs present but not perceived; maximum speed of 116.7 kmph; private optimum	75 (196.9)	100 (75.3)	116.7 (237.0)	509.2	98.8	227
Maximum speed of 116.7 kmph; minimum speed of 83.3 kmph; private optimum	83.3 (185.1)	100 (46.5)	116.7 (185.1)	416.7	100	185

Note: for costs a reference value zero has been chosen in the upper row

To achieve a more drastic adjustment, speed limits have to be applied. Thus we conclude that information provision on speed-variance related costs helps, but that it is not sufficient to reach optimum speeds; it is a third-best policy.

So far we have ignored that in addition to the safety related externalities other externality types, as discussed in Section 2, will also play a role. If these are integrated in the analysis of the present section, some additional observations can be made. In terms of the analysis of Appendix 2, the introduction of interdependencies among drivers has important implications. By the interdependencies the cost functions are reshaped and shifted in such a way that the privately optimum speed levels sp_i^* are closer to each other, and the same holds true for the socially optimum levels ss_i^* . This means that heterogeneity among drivers decreases, so that the inefficiency of uniform maximum speed limits will also be reduced. For example, with the introduction of interrelationships of speed limits, the case presented in Appendix 2, where $ss_1^* < sp_1^* < ss_2^* < sp_2^*$, may be trans-

formed into a case where the socially optimum speeds of both drivers would be lower than the privately optimum speeds so that we arrive at $\max(ss_1^*, ss_2^*) \leq \min(sp_1^*, sp_2^*)$. As explained in the Appendix, in this case the inefficiencies related to a uniform maximum speed are smaller. Thus we conclude that when the two types of externalities (related to both speeds and speed differences) are studied jointly, a substantial reduction in the social costs of transport can in principle be obtained by maximum speed limits, especially when maximum speed limits are combined with minimum speed limits.

A final remark is in order about the nature of the speed interrelationships between drivers. The interrelationships discussed here relate to safety considerations of drivers. Another relevant speed interrelationship in reality concerns congestion. The mechanism underlying congestion is, however, different from the mechanism presented here. It is clear that the analysis carried out in this paper does not directly apply to congested situations, since we assume that drivers are free to choose a certain speed. There is, nevertheless, a certain lesson to be learned. If the average driver would like to drive at speeds that are higher than the socially optimum level, a moderate level of congestion may not be as bad as it is often thought to be, since it would be a most effective way of reducing the speed of drivers towards the socially optimum speed (see also Shefer and Rietveld, 1997).

4. Concluding Remarks

Our conclusion is that with homogeneous drivers, a maximum speed limit (in conjunction with a system of fines) can be used to arrive at an efficient correction for externalities ignored by drivers who only consider private costs. However, when drivers are heterogeneous, a uniform maximum speed limit is only a second-best instrument to correct for transport externalities.

Another relevant case occurs when, for safety reasons, the private and external costs of drivers not only depend on their own speed, but also on the speeds of other drivers. In this situation a uniform maximum speed limit does not lead to the social optimum; it has adverse effects, because it negatively affects the speed choice of the slower drivers. When, however, the maximum speed limit is combined with a minimum speed limit, a more favourable result occurs.

Drivers may not be aware of the risks of speed differences. We show that information provision on the risks of both slow and fast driving helps to reduce the total accident costs. However, since the variance related costs are partly external, the speed adjustments induced by information provision do not go far enough.

Minimum speed limits are used nowadays in some countries (for example, in the USA there is a minimum speed of 40 mph on some highways). The legal formulation of the minimum speed limit should make clear that the limit does not apply in special situations such as gridlock, extreme weather, and so on. Therefore, one might prefer *recommendations* on minimum speeds instead of *stipulations*. The disadvantage of a

recommendation is, however, that drivers may become confused when they are confronted with speed instructions of various degrees of strictness. In addition, one would like to have an effective instrument to keep cars that do not drive faster than some 60 kmph (for example, due to mechanical disorder) from minimum-speed highways.

A possible objection to minimum speed limits on highways is that they might have an adverse effect. For example, it might lead to safety problems because slow drivers may feel unsafe when they are forced to drive faster. The obvious advice would be that these drivers use other roads where lower speeds are allowed. Minimum speed limits could only apply to *certain types* of roads in a road network, never to a network as a whole.

Another relevant case of speed differences concerns special vehicle types such as trucks. In several European countries trucks and buses have to obey a uniform special maximum speed limit of 80 kmph.⁵ This leads to a rather large speed variance on expressways,⁶ where other cars are allowed to drive much faster. If one wishes to maintain the maximum speed limit for trucks the solution would be (as is done in some countries) to prohibit trucks from overtaking (using the second lane). This not only has a beneficial effect on congestion, but also leads to a reduction of speed variance on the second lane. Obviously this overtaking prohibition has a similar effect to a minimum speed limit on the second lane.

Since heterogeneity of drivers and cars is considerable, one may consider the possibility of a more flexible speed regulation that would allow for different speeds, based on the technical features of cars (low emission cars would be allowed to drive faster). Note, for example, that on motorways in many countries trucks are already confronted with different speed limits from passenger cars. A broader approach would be to offer drivers the option to buy a permit to drive at higher speeds. This would be an interesting option for drivers with high values of time. From the perspective of a private road owner who wishes to maximise the profits of his operations such a diversification of the services offered would be attractive. Such a strategy should not interfere with the aims to correct for external effects, however. This could be achieved by allowing higher speeds only for cars that comply with certain strict emission standards. However, since speed differences are positively related to accident rates, the possibility for a differentiation in speed limits is restricted. For motorways, special pay lanes allowing higher speeds than on ordinary lanes might be a way to implement this idea.

⁵ This has been a measure where speed-difference related costs were ignored.

⁶ Similar examples of a high speed variance may occur with tractors and (motorised) bicycles on interurban roads. Here, too, the joint use of these roads by drivers with different speeds leads to high accident costs. In some countries this is solved by a separation of slow and fast modes: slow modes are prohibited from using the common road and are provided with a special lane for slow traffic (for example, a bicycle lane). This again has a similar effect to the formulation of a minimum speed limit on certain roads, plus the supply of an alternative route.

Appendix 1

Fines and speed limits

The minimally necessary effective level of the fine $p.f(s_i)$ at the level of the speed limit is exactly equal to the optimum level of the speed tax mentioned in Section 2. This is true because the above formulation of the effective tax level implies for speed $ss_i^* + \Delta$ just above ss_i^* :

$$p.f(ss_i^* + \Delta) > CP_i(ss_i^*) - CP_i(ss_i^* + \Delta).$$

The expression at the right-hand side equals the marginal private costs of speed at the social optimum (times -1), and at the social optimum these are equal to the marginal external costs of speed.

The optimality condition to determine the level of fines is formulated as a minimum condition. It contains many degrees of freedom to take other considerations into account. For example, the gap between $CP_i(s_i)$ and $CP_i(ss_i^*)$ would be an increasing function of speed in the range between s_i and sp_i^* , but at a decreasing rate. For speeds above sp_i^* the gap is even decreasing. Considerations of justice would, however, lead to a proportional or even a progressive structure such as $c.(s_i - ss_i^*)^h$, where $h=1$ in the case of a proportional structure, and $h>1$ in the case of a progressive structure.

Another consideration in the setting of the tax structure is the absorption of the costs of surveillance and the costs of collecting the fines. This may lead to a practice where small violations of the limit are left unfined (in some countries every driver knows he may violate the limit up to 10 km/h before the police will fine him), but it may also lead to a fine structure where a fixed component is included to cover the fixed costs of the administrative procedures involved.

Appendix 2

Social Costs and Maximum Speed Limits with Heterogeneous Drivers

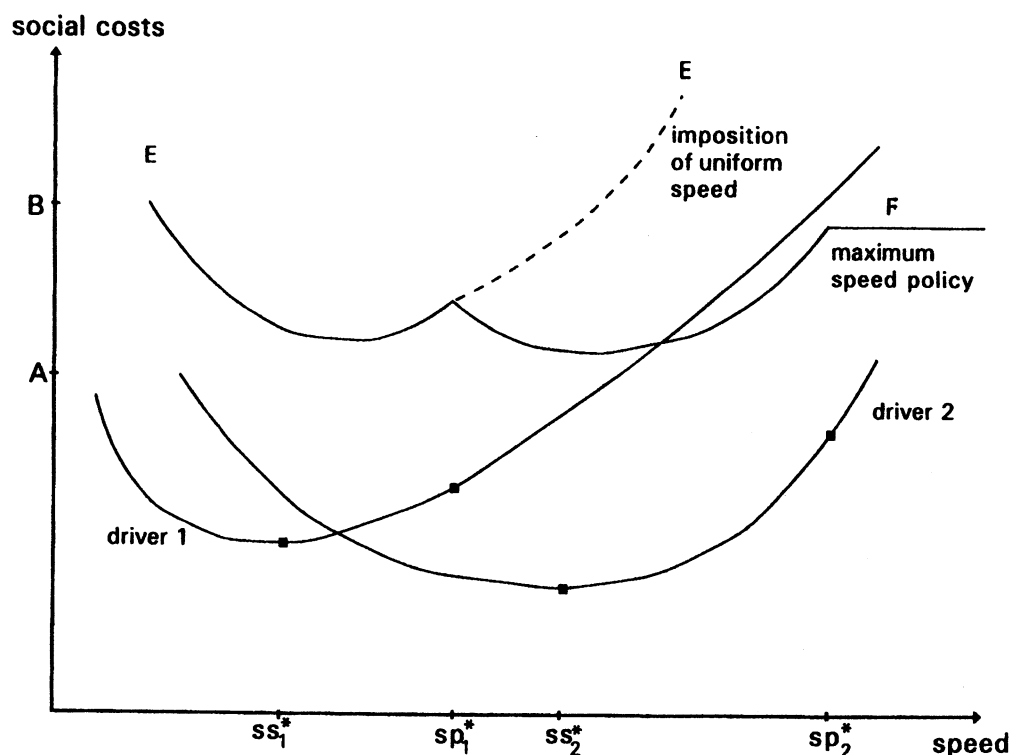
Consider the case of two drivers (see Figure 3). We assume that the following ranking of optimum social and private speeds holds:

$$ss_1^* < sp_1^* < ss_2^* < sp_2^*.$$

The second driver's social cost function has a location much more to the right, which may be an indication of a high value of time and/or a car type with low emission levels at high speeds.

The optimum level of social costs is $CP_1(x_1, ss_1^*) + CP_2(x_2, ss_2^*)$, and is represented by OA on the vertical axis. Without any regulation the social costs amount to $CP_1(x_1, sp_1^*) + CP_2(x_2, sp_2^*)$, represented as OB. Summation of the two cost curves yields the curve EE, which tells us what the social costs are when both drivers would have the same speed. Obviously, its minimum is above the social optimum OA, because of the imposition of an additional constraint.

Figure 3
Speed Limits and Optimum Speeds with Heterogeneous Road Users



The effects of the imposition of a *maximum speed* are represented by the EF curve. Starting from the right, a speed limit (denoted as s_1) will not affect speed choice as long as $s_1 \geq sp_1^*, sp_2^*$. Hence the social costs are constant in this interval. Reducing s_1 further leads to speed reactions of driver 2 and to a reduction of social costs. A minimum is achieved when the speed limit equals ss_2^* . A further reduction of s_1 to sp_1^* leads to an *increase* in social costs; the reason is that the limit is still too high to have a socially beneficial impact on driver 1, while on the other hand it forces driver 2 to travel at a speed that is even lower than its socially optimum level ss_2^* .

Only when the speed limit is reduced below sp_1^* will driver 1's contribution to social costs be favourably affected. In Figure 3, the curves have been drawn in such a way that total social costs achieve another (local) minimum between ss_2^* and sp_1^* . Note that with speed limits lower than sp_1^* , the two drivers have equal speeds. Hence, in this sec-

tion of the figure the curves EE and EF coincide. The non-convex shape of the EF curve means that when governments change maximum speed standards while not having complete information, this may lead to unexpected effects on social costs.

A system of fines may again be introduced to make sure that the speed limit is obeyed. In Figure 3 a limit equal to ss_2^* would imply that only driver 2 would be a potential violator. In a more general setting the fine necessary to enforce obeying the speed limit would have to be based on the maximum marginal external costs among the drivers for whom the speed limit is effective.

The case discussed here is characterised by a strong degree of heterogeneity in terms of speed behaviour among road users: the socially optimum speed of driver 1 is assumed to be higher than the privately preferred speed of driver 2. As illustrated in Figure 3, the performance of a general speed limit is rather low in this case. More favourable opportunities for maximum speed limits exist when heterogeneity among drivers is small. Consider for example, the case when the socially optimum speed of all drivers is lower than the privately preferred speed for all drivers. With two drivers this would imply:

$$\max(ss_1^*, ss_2^*) \leq \min(sp_1^*, sp_2^*).$$

In this case the possibility of a non-monotonous effect of speed limit reductions on social costs can be excluded. However, in this case speed limits will in general not lead to the achievement of the socially optimum cost level. This would only be possible when the socially optimum speeds of all drivers became the same.

References

- Baumol, W. J. (1972): "On Taxation and the Control of Externalities". *American Economic Review*, 62, 307-22.
- Baumol, W. J. and W. E. Oates (1988): *The Theory of Environmental Policy*. Cambridge: Cambridge University Press.
- Eskeland, G. S. (1994): "A Presumptive Pigovian Tax: Complementing Regulation to Mimic an Emission Fee". *The World Bank Economic Review*, 8, 373-91.
- Fildes B. N. and S.J. Lee (1993): *Road Environment, Behaviour, Speed Limits, Enforcement and Crashes*. New South Wales: Federal Office of Road Safety.
- Finch, D. J., P. Kompfner, C. R. Lockwood and G. Maycock (1994): *Speed, Speed Limits and Accidents*. Crowthorne, Berkshire: Transport Research Laboratory, report 58.
- Fowles, R. and P. D. Loeb (1989): "Speeding Coordination and the 55-mph Limit: Comment". *American Economic Review*, 79, 916-21.
- Hauer, E. (1971): "Accidents, Overtaking and Speed Control". *Accident Analysis and Prevention*, 3, 1-13.
- HCG (1990): *The Netherlands Value of Time Study*. The Hague: HCG.
- Jorgenson, F. and J. Polak (1993): "The Effect of Personal Characteristics on Drivers' Speed Selection; an Economic Approach". *Journal of Transport Economics and Policy*, 27, 237-52.
- Klein, J. A. P. (1993): *Luchtverontreiniging; emissies door het wegverkeer*. The Hague: CBS, report M45.

- Lave, C. A. (1985): "Speeding Coordination and the 55-mph Limit". *American Economic Review*, 79, 926-31.
- Levy, D. T. and P. Asch (1989): "Speeding Coordination and the 55-mph Limit: Comment". *American Economic Review*, 79, 913-15.
- Rienstra, S. and P. Rietveld (1996): "Speed Behaviour of Car Drivers, a Statistical Analysis of Acceptance of Changes in Speed Policies in the Netherlands". *Transportation Research D*, 1, 97-110.
- Shefer, D. and P. Rietveld (1997): "Congestion and Safety on Highways, Towards an Analytical Model". *Urban Studies*, 34, 679-92.
- Snyder, D. (1989): "Speeding Coordination and the 55-mph Limit: Comment". *American Economic Review*, 79, 922-25.
- Solomon, D. (1964): *Accidents on Main Rural Highways Related to Speed, Drivers and Vehicle*. Washington DC: US Department of Commerce.
- Sterner, T., C. Dahl and M. Franzén (1992): "Gasoline Tax Policy, Carbon Emissions and the Global Environment". *Journal of Transport Economics and Policy*, 26, 109-19.
- Transportation Research Board (TRB) (1995): *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use*. TRB: Special Report 245.

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